

# **A Performance Assessment of a Tactical Airborne Separation Assistance System Using Realistic Traffic Flows**

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## **I. Introduction**

This paper presents the results from a study that investigates the performance of a tactical Airborne Separation Assistance System (ASAS) in en route airspace, under varying demand levels, with realistic traffic flows. The ASAS concept studied here allows flight crews of equipped aircraft to perform separation from other air traffic autonomously.

This study addresses the tactical aspects of an ASAS using aircraft state data (i.e. position and velocity) to detect and resolve projected conflicts. In addition, use of a conflict prevention system helps ASAS-equipped aircraft avoid maneuvers that may cause new conflicts. ASAS-capable aircraft are equipped with satellite-based navigation and Automatic Dependant Surveillance Broadcast (ADS-B) for transmission and receipt of aircraft state data.

In addition to tactical conflict detection and resolution (CD&R), a complete, integrated ASAS is likely to incorporate a strategic CD&R component with a longer look-ahead time, using trajectory intent information. A system-wide traffic flow management (TFM) component, located at the FAA command center helps aircraft to avoid regions of excessive traffic density and complexity. A Traffic Alert and Collision Avoidance System (TCAS), as used today is the system of last resort. This integrated approach avoids sole reliance on the use of the tactical CD&R studied here, but the tactical component remains a critical element of the complete ASAS.

The focus of this paper is to determine to what extent the proposed tactical component of ASAS alone can maintain aircraft separation at demand levels up to three times that of current traffic. The study also investigates the effect of mixing ASAS-equipped aircraft with unequipped aircraft (i.e. current day) that do not have the capability to self-separate. Position and velocity data for unequipped aircraft needs to be available to ASAS-equipped. Most likely, for this future concept, state data would be available from instrument flight rules (IFR) aircraft, equipped with at least ADS-B transmission capability.

The objective is to reduce the number of losses of separation to a minimum and investigate the limits of tactical-only CD&R. Thus, the objective is not, expressly, to achieve zero losses of separation with tactical ASAS because this is one component of an integrated ASAS.

## **II. Motivation/ Significance**

The ASAS concept analyzed here has the potential to allow the flight crew of equipped aircraft to assume responsibility for separation during the en route phase of flight. This can potentially increase airspace capacity that today is primarily limited by the workload constraints of air traffic controllers.

The concept may also increase the flow of traffic through an airport by enabling aircraft to meet a required time of arrival (RTA) at the arrival fix. Accurately meeting an RTA

evens out traffic flow and reduces spacing uncertainty. The capability to meet an RTA is a key element of the Next Generation Air Transportation System (NextGen) trajectory-based operations (TBO) concept, as defined in the Joint Planning and Development Office (JPDO) concept of operations (CONOPS) [1].

In addition to capacity gains, ASAS may also increase the efficiency of flight by allowing more direct routing compared with the routes in use today. Airlines and flight crews gain flexibility to modify routes during flight while remaining within National Airspace System (NAS) constraints.

The ASAS concept directly addresses transition path issues between today's IFR operations to a future state where IFR traffic safely inter-operates with self-separating ASAS operations.

### **III. Concept Outline**

The concept investigated in this study makes use of an automated, flight-deck based system for CD&R, combined with a conflict prevention system to prevent aircraft maneuvers from creating new conflicts. The KB3D [2] algorithm was used for tactical CD&R, combined with a conflict prevention system known as Predictive-ASAS (P-ASAS) [3]. This combination is referred to as Tactical ASAS in this report.

Upon detection of a potential conflict, a flight-deck display indicates one or more possible resolution maneuvers to the pilot. The P-ASAS provides information that the pilot can use to avoid additional, secondary conflicts (e.g. within the ensuing 3 minutes). Therefore, the pilot makes the final selection of maneuver.

ASAS aircraft are equipped with a Flight Management System (FMS) with the capability to meet an RTA. This FMS enables the aircraft to meet flow-management constraints. These constraints may include required time and position of airspace-region crossing points and required arrival time at an airport arrival fix.

Thus, using ASAS, in properly equipped aircraft, trained crews can assume responsibility for traffic separation. Such crews would be free to modify their flight path in real time, without approval from an air traffic controller as long as the trajectory meets any flow-management constraints.

The concept necessitates that self-separating flights operate under a new set of flight rules called autonomous flight rules (AFR). The AFR flights are required to maintain separation from all other aircraft. Using a set of priority rules, one aircraft in the pair in conflict is required to maneuver first, with the other aircraft maneuvering if the situation becomes urgent.

In a mixed equipage environment, AFR aircraft are also required to maintain separation from aircraft operating under IFR and must give priority to such aircraft. Air traffic controllers would issue flow-management constraints to all aircraft and continue to

provide separation among IFR aircraft, accommodating those operators who choose not to equip for AFR. In all likelihood, controllers would need to be aware of the presence of AFR aircraft and avoid maneuvering IFR aircraft into short-term conflicts with AFR. However, controller actions in a mixed equipage environment are not within the scope of this study.

#### IV. Technical Approach

The technical approach for this study was to investigate the performance of Tactical ASAS using the Traffic Manager (TMX) simulator [4]. TMX was developed by the National Aerospace Laboratory of the Netherlands (NLR) and enhanced by NASA Langley Research Center.

TMX was developed for use in studies of aircraft based concepts in future ATM environments. TMX can be used as one component of a real-time simulation in an air-traffic laboratory or as a stand-alone desktop simulation. This study used TMX as a stand-alone, non real-time simulator without any human in the loop interaction.

Currently, in stand-alone mode, TMX runs on a single workstation and can simulate up to 2000 airborne aircraft. This limits experiments to the scope of e.g. one ATC center at up to three times current demand levels. Figures 1 and 2 are screenshots of the TMX graphical user interface.

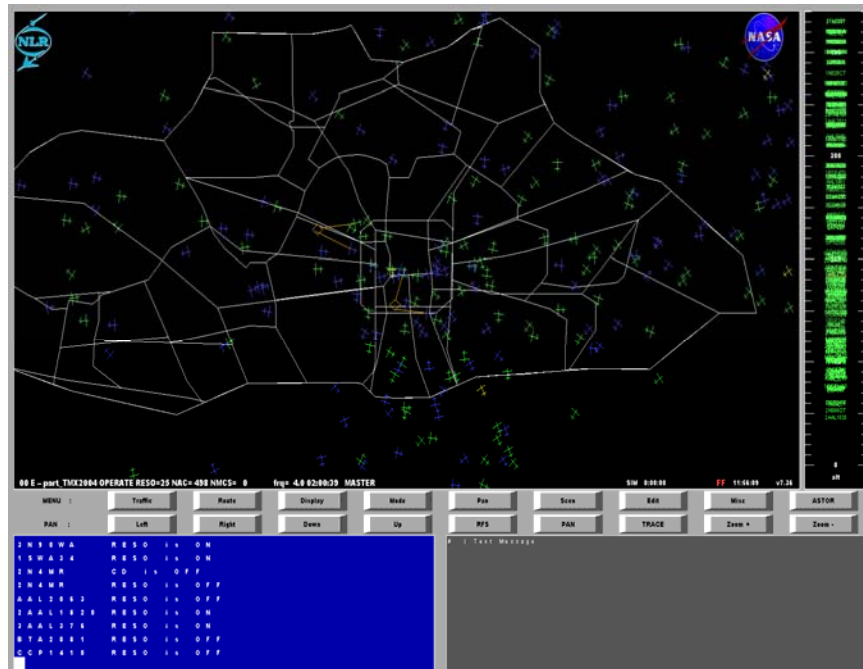


Figure 1. TMX user interface showing AFR aircraft (green) and IFR aircraft (blue).

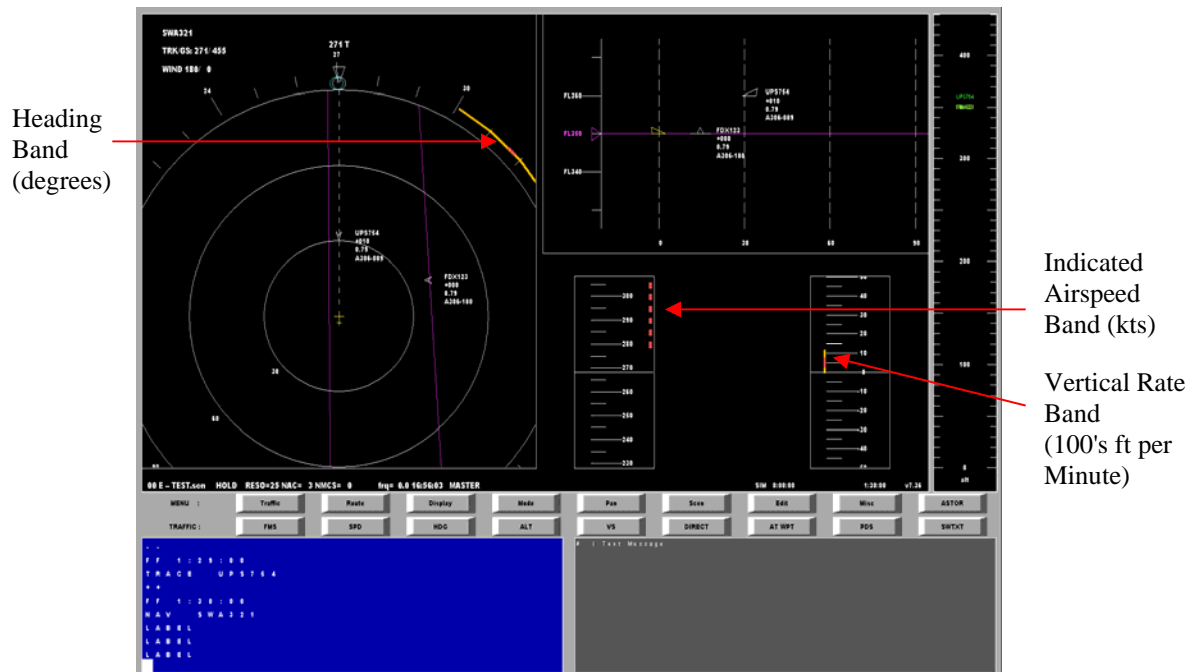


Figure 2. TMX conflict prevention bands for heading, speed and vertical rate. (Yellow band indicates a predicted conflict within 5 minutes, red within 3 minutes.)

Aircraft within TMX may be equipped with some or all of the following features:

- auto-flight functionality
- four-dimensional flight management system (FMS)
- RTA capability
- Automatic Dependant Surveillance-Broadcast (ADS-B)
- CD&R
- P-ASAS

TMX has an aircraft dynamics model that includes the effect of wind and uses aircraft performance data from the Base of Aircraft Data (BADA). The Eurocontrol Experimental Centre in Brétigny, France developed and currently maintains BADA. TMX has a simple pilot model that contains decision-making logic (e.g. choice of conflict resolution maneuver) and includes pilot reaction times.

The KB3D CD&R algorithm was implemented within TMX for use in this study. KB3D is a tactical, state-based CD&R algorithm developed in the Safety Critical Avionics Systems Branch at NASA Langley Research Center [5].

The KB3D algorithm provides one or more horizontal and vertical resolutions by calculating analytical solutions using linear trajectory projections. KB3D considers two aircraft in conflict, solving the most urgent conflict first. Resolutions are independent, so only one aircraft needs to maneuver and resolutions are coordinated so both aircraft can maneuver.

An advantage of an analytic approach is that the underlying math is amenable to formal proof of correctness. This allowed the mathematical properties of KB3D to be

extensively studied and formalized in the Prototype Verification System (PVS) [6]. Formal proof using PVS guarantees that the algorithm will provide a resolution; however, KB3D does not check the resolution maneuvers for physical feasibility.

## V. Simulation Setup

The airspace region used for this study is Fort Worth Center (ZFW) (see figure 3). All aircraft departing from, flying through or landing within ZFW are included in the simulation. Figure 4 shows the notional elevation view of the en route airspace defined for this experiment, with altitude bounds from 17,000 ft to 60,000 ft. The CD&R and P-ASAS systems were functional from departure, through transition into the experiment volume and then turned off as aircraft exit from the experiment volume. Flights were deleted from the simulation as they descended through 5000 ft.

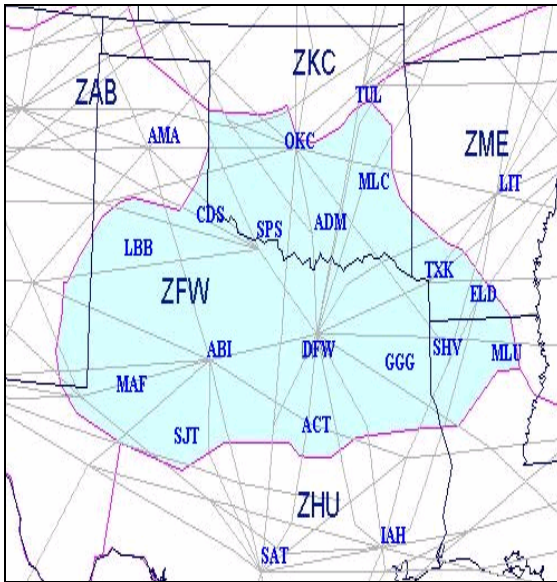


Figure 3. Fort Worth Center airspace.

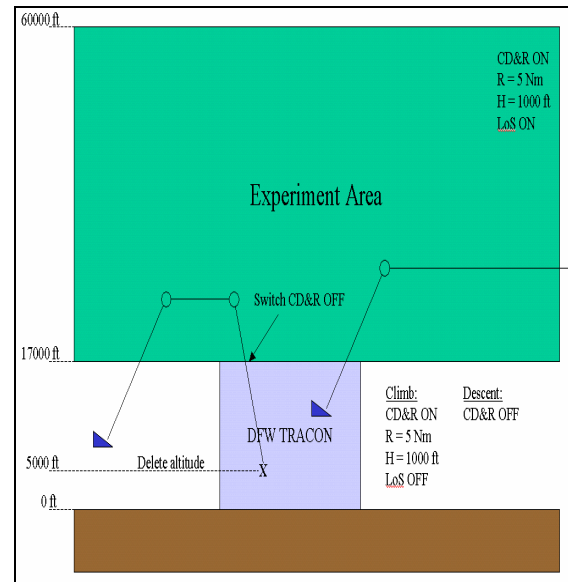


Figure 4. Experiment airspace.

## VI. Flight Data Sets

The flight trajectories that were recorded by ETMS on 19 February 2004 form the basis for the flight data sets used in this study. Thus, simulated traffic flows are realistic, based on actual recorded data. The simulated traffic flows retain the complexity of the traffic flows within ZFW center.

The flight data sets consisted of IFR-only, AFR-only and mixed scenarios and range from one to three times current demand levels. The increased demand levels were created by cloning the baseline-recorded trajectories and rescheduling as described below. Table 1 shows the number of flights in each of the data sets.

	<b>IFR baseline schedule</b>	<b>1X AFR</b>	<b>2X AFR</b>	<b>3X AFR</b>	<b>1X IFR + 1X AFR</b>	<b>1X IFR + 2X AFR</b>
<b>Total flights</b>	4,079	4,079	8,158	12,237	8,158	12,237

Table 1. Flight data sets used in simulation.

The IFR flights use the as-flown trajectories that were derived from the ETMS radar track data (TZ) messages. The IFR flight schedule is almost exactly as flown, with slight adjustments in departure times; these were made as necessary to ensure a minimum spacing of 70 seconds between aircraft arriving at the same arrival fix.

The AFR flights are based on the same ETMS data converted to great-circle routes and are scheduled to meet 70 seconds spacing at the arrival fix. AFR flights flew fuel-optimal trajectories based on BADA performance data and were not constrained by the current cardinality rules for flight altitude levels.

For the mixed flight schedules, AFR flights were inserted into gaps in the IFR arrivals streams at each fix to maintain a minimum of 70 seconds spacing.

The use of 70 seconds spacing ensures that the minimum distance between aircraft at the airport arrival fixes is approximately 5 nm. For simplicity of scheduling, generic arrival fixes replace the actual arrival fixes. Four generic fixes are equally spaced on a 40 nm radius circle centered on each airport. This four-corner post arrangement is close to the actual fix arrangement used by many airports (an example is DFW).

Scripted conflicts were not included in this experiment. Rather, all aircraft departed their origin airports at their nominal time to meet their RTA at the arrival fixes. Conflicts developed naturally without pre-determination. The result is that the ASAS system is subjected to a full range of traffic situations and geometries that ranged from simple to quite complex. The experiment was therefore a blind test of whether the conflict management algorithms and procedures were robust to all of the conditions that were encountered.

## VII. Results and Discussion

The results presented below were obtained from simulations that employed error-free surveillance data. The simulation test cases used actual wind data from 19 February 2004, without errors between actual and predicted winds. The modeling included aircraft dynamic performance, with error-free FMS performance. Pilot response times were included, but were not randomized. TMX has the ability to include randomized errors for all modeled systems, including wind measurement and prediction errors; the performance of ASAS with realistic errors is the subject of on-going and future research.

The results analysis is organized into the following sections: first, traffic densities; next, conflicts and losses of separation; finally, flight efficiency.

## Traffic Densities

Table 2 shows various measures of traffic density in the simulation. By design, the 24-hour demand was twice and three times the baseline. The number of aircraft airborne at any time varies according to the schedule and the peak does not reach exactly twice and three times the demand. The peak flight density multiplier is somewhat less than the 2X and 3X input demand because flights are re-scheduled to ensure a minimum of 70 seconds between aircraft at the airport arrival fixes.

	IFR baseline schedule	2X AFR		3X AFR	
		Flights	Multiple of baseline	Flights	Multiple of baseline
<b>Total flights in 24 hrs</b>	4,079	8,158	<b>2X</b>	12,237	<b>3X</b>
<b>Peak flights in simulation</b>	516	1,035	<b>2X</b>	1,519	<b>2.9X</b>
<b>Peak flights ZFW</b>	126	241	<b>1.9X</b>	326	<b>2.6X</b>
<b>Mean flights ZFW in 24 hrs</b>	61	114	<b>1.9X</b>	171	<b>2.8X</b>

Table 2. Number of aircraft in the simulation.

The busiest sector within ZFW was ZFW4201 High sector. This sector had a maximum count of 46 aircraft simultaneously in the sector for the 3X demand compared with 17 for the baseline number of airborne aircraft. This is well in excess of the current maximum capacity of 20 aircraft set by the monitor alert parameter (MAP) value (see figure 5).

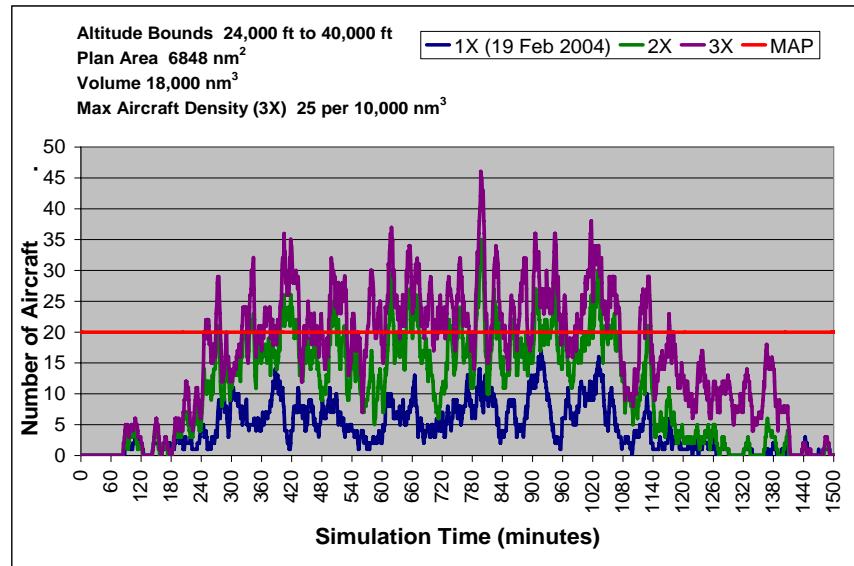


Figure 5. Number of aircraft in busiest ZFW sector (ZFW4201 High).

A discussion of Tactical ASAS performance follows in the next sections, in terms of conflicts and losses of separation and efficiency of flight. Note, however, that traffic



densities outside of ZFW center are less than the actual traffic densities because not all flights in the NAS could be included in the simulation. For this reason, conflict data was analyzed within the experiment volume only. Data outside of the experiment volume does not represent the performance of Tactical ASAS at full traffic densities. Likewise, efficiency data is interpreted with the caveats stated in the relevant section.

## Conflicts and Losses of Separation

The terms used and values of key parameters are presented prior to discussion of results.

Definitions of terms are:

- Conflict: a predicted loss of separation within a given look-ahead time (*One pair of aircraft in conflict count as two conflicts*).
- IFR to AFR Conflicts: conflicts detected first by IFR aircraft
- AFR to IFR Conflicts: conflicts detected first by AFR aircraft
- LoS: Loss of Separation (*One pair of aircraft count as one loss*).
- CPA: Closest Point of Approach between an aircraft and any other.

The criteria used to report a LoS are:

- Aircraft closer than 5 nm lateral distance and 900 ft altitude, for more than 10 seconds duration.

The protected zone around an aircraft to detect a conflict is:

- AFR to AFR: 5.1 nm lateral, 950 ft altitude at 300 seconds look-ahead time.
- AFR to IFR: 6.1 nm lateral, 1,150 ft altitude at 300 seconds look-ahead time.
- IFR to AFR: 5.1 nm lateral, 950 ft altitude at 180 seconds look-ahead time.

The zone around an aircraft for conflict resolution is:

- AFR to AFR: 5.2 nm lateral, 1100 ft altitude at 300 seconds look-ahead time.
- AFR to IFR: 6.2 nm lateral, 1300 ft altitude at 300 seconds look-ahead time.

Notes:

1. The conflict resolution zone was larger than the protected zone to allow some uncertainty buffer, increasing the probability that the conflict would be resolved by the resolution maneuver.
2. A larger protected zone between AFR to IFR aircraft and a longer look-ahead time relative to IFR to AFR was used. The intent was that the AFR aircraft would detect and resolve the conflict with the IFR aircraft before the ground controller was alerted to the impending conflict.
3. The vertical separation minima is 900 ft rather than the current vertical separation minima of 1000 ft, since aircraft may be up to 100 ft from assigned altitude due to altimeter inaccuracy.

Table 3 summarizes the results obtained from analysis of data logged by TMX within the experiment volume described in the experiment set up section.

<b>ETMS based</b>	<b>1X IFR (from ETMS)</b>	<b>1X AFR</b>	<b>2X AFR</b>	<b>3X AFR</b>	<b>1X IFR + 1X AFR</b>	<b>1X IFR + 2X AFR</b>
<b>Flights</b>	4,079	4,079	8,158	12,237	8,158	12,237
<b>Conflicts</b>	NA/	1,021	4,155	9,257	4,751	12,228
<b>IFR_AFR conflicts</b>	NA/	N/A	N/A	N/A	628	1,144
<b>Number of LoS</b>	N/A	0	3	25	26 (2 AFR/ AFR)	58 (25 AFR/ AFR)
<b>Resolved Conflicts (%)</b>	N/A	100.0%	99.9%	99.5%	98.9%	99.1%

Table 3. Conflicts and losses of separation within experiment volume.

The results show that Tactical ASAS, using the KB3D CD&R algorithm, in combination with P-ASAS can prevent all losses of separation for the 1X demand scenario if all aircraft are AFR flights. For the 2X AFR scenario, one of the three LoS is attributable to Tactical ASAS. The LoS was of short duration with a separation of 4.5 nm at the CPA. The other two LoS are caused by an experiment set up issue that is discussed in the next section.

The number of LoS increases for the 3X AFR scenario. However, all but four of the LoS had a CPA larger than 3 nm. The closest encounter had a CPA of 0.18 nm, but in this case, the vertical separation was 818 ft, which is just under the 900 ft vertical separation criteria used for this study.

The mixed 1X IFR + 1X AFR case has many IFR to AFR conflicts. Note that this would require the IFR aircraft to take action to avoid the AFR aircraft, which is contrary to the concept design. In addition, considerably more losses of separation occurred compared with the all-AFR scenario with the same 2X demand.

The mixed 1X IFR + 2X AFR case has one-third more conflicts and more than twice as many losses of separation than the all-AFR case at the same 3X demand level.

The causes for many of the LoS are understood; discussion of causes and some suggestions for improving the performance of Tactical ASAS follows.

## Discussion of Causes of Loss of Separation

The list below identifies the causes of the LoS for the 2X AFR, 3X AFR and the 1X AFR + 1X IFR scenarios and the number of cases that are attributed to each cause. (The 1X AFR + 2X AFR scenario has not been analyzed in detail.) Note that a LoS may have more than one cause.

## **1. AFR aircraft maneuvers into short-term conflict (24 LoS)**

The conflict prevention system should prevent maneuvers that result in conflicts with predicted LoS in less than 3 minutes. This was not always the case, particularly with climbing and descending aircraft. P-ASAS assumes linear trajectory propagation and linear climb and descent profiles. Actual aircraft may be changing speed or heading and often do not climb or descend linearly. Aircraft in the simulation above 18,000 ft are climbing or descending at constant Mach. Since groundspeed reduces with altitude at constant Mach (in the troposphere), this results in a flight path that curves in the vertical Cartesian plane. In addition, an aircraft climbs more slowly near its maximum altitude limit. For these reasons, P-ASAS may incorrectly predict aircraft trajectory, leading to incorrect conflict bands.

Aircraft sometimes maneuver into short-term conflict for a different reason; the pilot model occasionally selects resolution maneuvers that contradict the P-ASAS conflict prevention system. In some circumstances, this problem is unavoidable, because conflict bands may indicate that all resolution maneuvers provided by KB3D result in a secondary conflict.

## **2. CD&R and P-ASAS inactivate (16 Los)**

The experiment was purposely set up to turn off CD&R and P-ASAS below 17,000 ft, because the concept studied is for en route airspace. Once turned off, CD&R and P-ASAS are not turned on again. Thus, an unintended side effect results where one aircraft descends below the boundary and then levels off into a short-term conflict. An aircraft can likewise descend below the boundary during the climb phase of flight because of a conflict maneuver and then resume climbing above 17,000 ft and cause short-term conflicts throughout the remainder of the flight.

## **3. Poor resolution choice (14 LoS)**

The pilot model is not sophisticated and can occasionally select a maneuver that is a poor choice or that takes the aircraft into an irretrievably complex situation. KB3D offers a choice of resolution maneuvers for the two aircraft in conflict, independent of the trajectories of other aircraft; the human pilot, supported by P-ASAS selects the most appropriate resolution.

## **4. KB3D fails to predict a conflict in time to prevent LoS (11 LoS)**

KB3D sometimes detects a conflict with fewer than 3 minutes to LoS. In a few cases, only seconds remained before LoS, which is too short a time to resolve the conflict. This problem occurs mainly with climbing and descending aircraft. The KB3D algorithm assumes linear trajectory propagation and linear climb and descent profiles. For the same reasons as explained for cause 1, this can lead to

inaccurate prediction of the aircraft trajectory. Consequently, prediction error can cause KB3D to detect conflicts too late to prevent a LoS.

**5. KB3D does not continue to provide resolutions once aircraft are in LoS (6 LoS)**

The current design of KB3D prevents does not calculate resolutions if the aircraft in conflict move into LoS. This problem can prolong the LoS, lead to a closer encounter and potentially lead to a further LoS with additional aircraft. For AFR to IFR cases where a 6 nm protected zone is used, KB3D stops providing resolutions once the aircraft are closer than the 6 nm protected zone even though the separation criteria for LoS has not been violated. This is because KB3D does not currently distinguish between an additional buffer zone and the actual separation criteria.

**6. IFR aircraft maneuvers into short-term conflict with AFR (6 LoS)**

The simulated IFR aircraft currently fly ETMS recorded trajectories. No mechanism is included in the simulation to prevent IFR aircraft from creating short-term conflicts.

**7. KB3D does not take into account aircraft performance (3 LoS)**

While geometrically correct, KB3D may provide a resolution maneuver that is beyond the capabilities of the aircraft. The aircraft may not be able to respond quickly enough, or the speed or the requested altitude may not be feasible. The resolution maneuver may sometimes require an aircraft to climb when it is near the aircraft altitude ceiling

The most common cause of LoS was a failure to prevent an AFR heading or altitude change from causing a short-term conflict. This cause may be due to a failure of the P-ASAS system to predict conflict bands or a failure of the pilot model to consider the bands.

Improvements to P-ASAS may be possible. Currently, TMX uses a geometric calculation for predicting conflict bands, similar but not the same as the KB3D algorithm uses for conflict resolution. The KB3D calculations can be formulated to determine conflict bands. This would be preferable for consistency with the resolution maneuvers. Using realistic assumptions for climb and descent profiles can improve trajectory prediction. Using buffer zones that are larger for aircraft not in level flight can better account for uncertainty.

Improvements to the pilot model may prevent some of the LoS where the model selects a maneuver that fails to consider the conflict bands. An indication of the maneuver with the longest time to LoS could assist the human pilot in making a decision and facilitate a better simulation model.

The second most common cause is a problem with simulation set up; Tactical ASAS is turned off below 17,000 ft. The experiment set up problem will be fixed for future studies.

The third most common cause is a poor choice of resolution, which can be attributed to an unsophisticated pilot model. Given a choice of maneuver from KB3D, a human pilot may have avoided the LoS by selecting a better choice of resolution maneuver. Some measure of traffic complexity in the region of the proposed maneuver might facilitate a better choice of maneuver. This would enable the pilot model in a simulation to make a better choice and might be a useful aid to a human pilot who is using ASAS.

Solutions to the remaining causes of LoS are also under consideration. These include enhancements to KB3D to improve trajectory prediction and to continue providing resolutions for aircraft in LoS. Checking of resolutions for physical feasibility is an obvious enhancement e.g. for aircraft near their altitude ceiling a climb is not a good choice of resolution. In this case, a heading change or descent would be the better choice.

A version of KB3D that uses some knowledge of aircraft intent is being designed. Conflicts may reduce if a strategic component to ASAS is included; this should lead to a corresponding reduction in LoS.

Strategic ASAS cannot prevent all short-term conflicts that arise from unplanned maneuvers (e.g. for conflict resolution maneuvers, intent data may not be available). Therefore, in a mixed equipage environment controllers may be required to avoid vectoring IFR aircraft into short-term conflicts with AFR aircraft.

## **Efficiency**

NAS wide simulation with full traffic densities over all regions of airspace is the best means to obtain reliable efficiency metrics. This is not possible using TMX, because TMX currently has a limit of 2000 airborne flights. At three times current demand levels, around 15,000 to 20,000 flights may be airborne in the NAS at the peak time.

Interpretation of results relating to efficiency is subject to the following caveats:

1. The AFR results overstate the efficiency of flight because full traffic density is not achieved outside of the experiment volume.
2. The IFR results are from simulation of actual recorded trajectories that include all conflict resolution maneuvers. These trajectories are from the real NAS, so all IFR aircraft experienced the full traffic density throughout the flight. AFR flights experienced full traffic density in the experiment area only. It is therefore not valid to compare IFR and AFR flight efficiencies.

3. IFR flights may purposely deviate from great-circle routes to follow a more wind optimal route or to avoid restricted airspace, weather or turbulence. Therefore, attributing the entire IFR distance penalty to restricted air-routes and controller resolution advisories is not valid.
4. The scope of this study was en route, so Tactical ASAS is active from departure fix until the aircraft leaves the experiment volume. Consequently, the efficiency metrics do not include the arrival or departure flight segments.

However, given the caveats, the simulation results show some interesting trends, as analyzed in the following sections.

### **Distance, Time and Fuel**

Table 4 presents the mean increase in average flight distance, time of flight and fuel used for the IFR and AFR-only scenarios. (The efficiency of the mixed equipage scenarios was not analyzed).

The basis for comparison is the same aircraft flying an unimpeded great circle route, using a fuel-efficient trajectory computed by TMX. The IFR and AFR flights are not compared directly for reasons explained above. The data are for the flight trajectory from departure fix to the arrival fix.

	<b>Distance (nm)</b>	<b>Time (seconds)</b>	<b>Fuel (lbs)</b>
<b>IFR</b>	17.0 (2.5%)	-110.7 (-1.9%)	500.0 (5.8%)
<b>1X AFR</b>	2.5 (0.4%)	11.5 (0.2%)	200.0 (2.4%)
<b>2X AFR</b>	6.9 (1.0%)	45.3 (0.7%)	300.0 (4.0%)
<b>3X AFR</b>	12.1 (1.8%)	86.7 (1.4%)	500.0 (5.4%)

Table 4. Mean increase in flight distance, time and fuel used.  
(Compared to unimpeded great-circle routes.)

The IFR flight distance was somewhat more than the great circle distance, with a significant excess fuel burn. However, the IFR flights actually had a mean flight time that was less than the unimpeded great circle flights. Therefore, IFR flights are flying somewhat faster than the TMX computed fuel-efficient speed. In addition, the excess fuel-burn might be partially due to IFR aircraft flying at altitudes that are not fuel-optimal because of TFM constraints.

The 1X AFR mean excess flight distance and excess fuel burn was small compared to the unimpeded flights. For AFR flights, this excess is the penalty that arises from conflict resolution maneuvers. The penalty increases as the demand level increases as expected.

### **RTA Capability**

Table 5 shows the ability of aircraft to meet an RTA at the arrival fix. Aircraft used the closed-loop algorithm modeled in TMX to adjust aircraft speed within their flight

envelope, to meet the RTA. This allows the aircraft to compensate for trajectory deviations caused by e.g. conflict resolution maneuvers.

	<b>% Flights +/- 5 Sec. of RTA</b>	<b>% Flights +/- 10 Sec. of RTA</b>
<b>1X AFR</b>	94.7	95.2
<b>2X AFR</b>	83.8	85.3
<b>3X AFR</b>	74.2	76.1

Table 5. Percentage of flights meeting RTA.

Almost 95% of aircraft meet the RTA within 5 seconds for the 1X scenario. However, the RTA meeting capability degrades as demand increases.

Figure 6 shows the probability distribution of the difference between RTA and actual time of arrival.

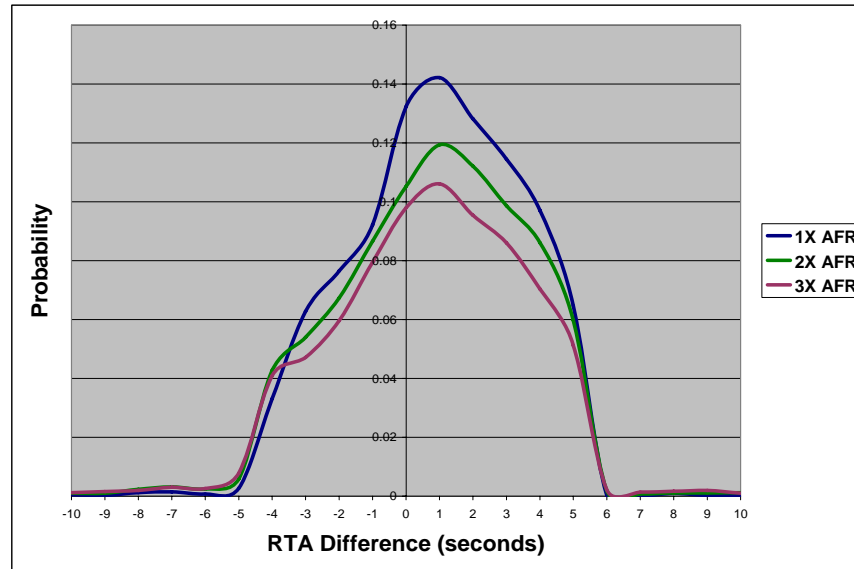


Figure 6. Difference in actual and required time at arrival fix.

Although most flights manage to meet the RTA within  $\pm 6$  seconds there are a number of outliers, particularly for the 3X demand. One cause is the increased number of conflicts as traffic densities increase. However, it may be possible to improve the RTA algorithm.

## VIII. Conclusions

The conclusions stated here, are valid for the experiment conditions defined, using the KB3D tactical CD&R algorithm combined with the TMX P-ASAS conflict prevention system. This study did not include system errors and did not include full traffic density outside of the Fort Worth center airspace. Some problems with the experiment set up led to some LoS not attributable to ASAS. Enhancements to the simulation set up, KB3D and P-ASAS should further improve performance.

The conclusions from this investigation are:

- The KB3D CD&R algorithm, using aircraft state data only, combined with the P-ASAS conflict prevention system, effectively prevented nearly all losses of separation up to twice-current demand levels for the AFR-only scenario. For the 1X AFR scenario, all conflicts were resolved without any losses of separation. For the 2X AFR scenario, 99.9% of conflicts were resolved with three losses of separation, only one of which was attributed to Tactical ASAS.
- At three times the current demand level and for mixed AFR and IFR scenarios, the number of losses of separation increases. Even so, 99.5% of conflicts are resolved for the 3X AFR case, 98.9% for the 1X IFR + 1X AFR case and 99.1% for the 1X IFR + 2X AFR case.
- For mixed AFR and IFR scenarios, some losses of separation resulted from IFR aircraft maneuvers that caused short-term conflicts with AFR. One solution could be to alert the controller to conflict-producing maneuvers by trial planning before requesting an IFR aircraft to maneuver. In addition, providing AFR aircraft with knowledge of the short-term intent of IFR aircraft may reduce the occurrence of controller IFR-to-AFR conflict alerts.
- The conflict resolution maneuvers provided by the KB3D CD&R algorithm are efficient; for the 1X AFR scenario, the maneuvers result in less than 0.5% mean increase in flight distance compared with the unimpeded great circle-route. At three times the current demand level the mean increase in distance is still only 1.8% compared to the great-circle route.
- AFR aircraft can meet their RTA at the arrival fix; 90% are within 5 seconds of the RTA, for the 1X AFR scenario. This degrades to 74% within 5 seconds for the 3X AFR scenario.

The reasons for many of the observed LoS are understood; others are still under investigation. An on-going research effort includes implementing improvements to the KB3D algorithm and changes to the TMX simulation code to improve performance of the Tactical ASAS component.

With these improvements, the number of losses of separation is expected to be further reduced. As one component of a complete ASAS, tactical CD&R is part of a layered approach to separation assurance, and is not expected to prevent all losses of separation when used alone.



## IX. References

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